

Dynamical scaling of $YBa_2Cu_3O_{7-\delta}$ thin film conductivity in zero field

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We study dynamic fluctuation effects of $YBa_2Cu_3O_{7-\delta}$ thin films in zero field around T_c by doing frequency-dependent microwave conductivity measurements at different powers. The length scales probed in the experiments are varied systematically allowing us to analyze data which are not affected by the finite thickness of the films, and to observe single-parameter scaling. DC current-voltage characteristics have also been measured to independently probe fluctuations in the same samples. The combination of DC and microwave measurements allows us to precisely determine critical parameters. Our results give a dynamical scaling exponent $z = 1.55 \pm 0.15$, which is consistent with model E-dynamics.

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INTRODUCTION

Since the discovery of the high-temperature superconductors, the normal-superconducting phase transition has attracted great interest, partially due to the larger critical region which comes from the high critical temperature and short coherence length of these materials.[1, 2] There has been a great deal of work investigating the phase transition in both zero and non-zero magnetic field.

In zero field, measurements of penetration depth,[3, 4] magnetic susceptibility,[5, 6, 7] specific heat[5, 8] and thermal expansivity[9] largely agree that the static critical exponent $\nu \simeq 0.67$ (governing the divergence of the correlation length $\xi \sim |T/T_c - 1|^{-\nu}$), and indicate that the phase transition in zero field belongs to the 3D-XY universality class. The dynamics of the transition, measured through transport properties, remains uncertain.

In principle conductivity measurements, which depend on the nature of the dynamics of the order parameter near T_c , can determine both the static critical exponent ν and dynamical critical exponent z governing the divergence of the fluctuation lifetime ($\tau \sim \xi^z$). The exponents ν and z are expected to be universal, but values extracted from conductivity measurements are not consistent. For example, DC conductivity measurements yield a wide range of values for critical exponents: $z = 1.25$ to 8.3 . [10, 11, 12, 13]

AC measurements can determine both the real and imaginary parts of the fluctuation conductivity, providing a stringent test of critical dynamics.[14, 15, 16, 17] Measurements over a broad frequency range allow us to probe the dynamical behavior of the system and directly measure the fluctuation lifetime.[15] However these experiments are difficult and seldom done, and the available results are inconsistent, with values of z ranging from 2 to 5.6. Booth *et al.* investigated the frequency-dependent microwave conductivity of $YBa_2Cu_3O_{7-\delta}$ (YBCO) films

above T_c and obtained $z = 2.3$ to 3 . [15] Nakielski *et al.* measured the conductivity of YBCO at low frequency (< 2 GHz) and obtained $z \approx 5.6$. [18] Osborn *et al.* did a similar experiment on $Bi_2Sr_2CaCu_2O_{8+\delta}$ and obtained $z \approx 2$. [19] For $La_{2-x}Sr_xCuO_4$, Kitano *et al.* found $\nu \approx 0.67$, $z \approx 2$. [20] There is clearly a lack of consensus on the dynamic fluctuations of the superconducting transition. Theory also lacks consensus, with strong arguments made for both $z = 1.5$ [21, 22, 23] and $z = 2$. [24] Further work to extract a value for z , and to establish its validity, is necessary.

When measuring microwave conductivity, one needs to apply a non-zero current. How the applied microwave current density affects the measured conductivity has not been systematically addressed. Recently Sullivan *et al.* argued that a finite-size effect at low current density was the reason for previous inconsistent results in DC measurements. [25] The question of whether the finite-size effect influences the AC measurement and the extracted critical exponents, as in DC measurements, inspires us to study the power dependence of the microwave fluctuation conductivity. We find that several length scales play a role in AC conductivity measurements, and only after their effects are properly accounted for can the underlying critical dynamics be understood.

Our samples are YBCO films ($d = 100$ nm to 300 nm thickness) deposited via pulsed laser deposition. AC susceptibility showed T_c of the films around 90 K with transition widths about 0.2 K. The resistivity of the films is about $120 \mu\Omega\text{-cm}$ at 2 K above T_c . The fluctuation conductivity was measured by a Corbino reflection technique. [15, 26, 27, 28]

Fig. 1 shows the measured complex fluctuation conductivity vs. frequency for various temperatures at two different microwave powers. The insets in Fig. 1 sketch the expected Fisher-Fisher-Huse (FFH) AC scaling behavior of the fluctuation conductivity near T_c . [14]

Fig. 1 shows that the measured fluctuation conductivity has significant and systematic deviations from FFH scaling. At high frequency, both magnitude and phase of the fluctuation conductivity look similar to the ideal

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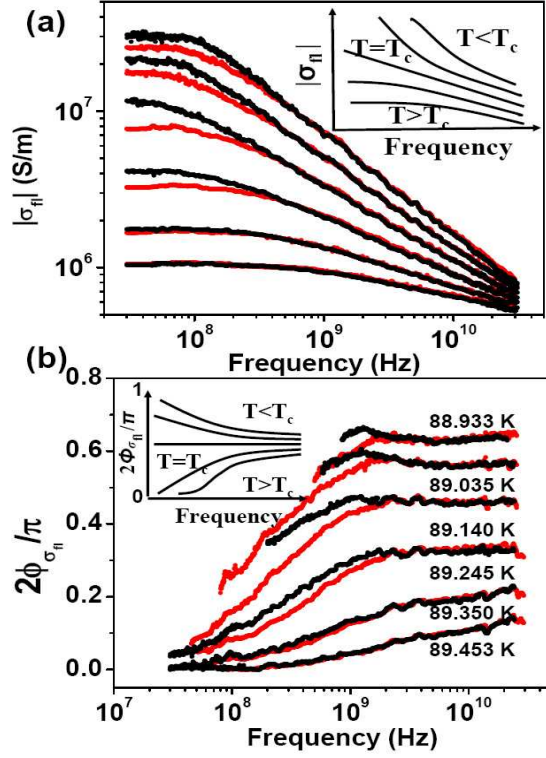


FIG. 1: (Color online) (a) Magnitude $|\sigma_{fl}|$ and (b) phase $\phi_{\sigma_{fl}}$ vs. frequency at various temperatures for a typical YBCO film (xuh139). The blue lines were measured with -22dBm power while the red lines were measured with -2dBm at the same temperature. The insets show sketches of Fisher-Fisher-Huse AC scaling.[14]

sketch. However, as frequency decreases the measured magnitude of the fluctuation conductivity below T_c saturates, instead of bending up. All of the phase isotherms below T_c tend toward zero, indicating ohmic response, instead of approaching $\pi/2$ at low frequency. These deviations are qualitatively similar to the low current-density deviations of E vs. J in DC measurements.[25]

Fig. 1 also shows that the applied microwave power affects the measured fluctuation conductivity, particularly at low frequencies. As frequency decreases, the higher applied microwave power decreases the magnitude of the fluctuation conductivity and depresses the phase. These phenomena can be explained using scaling theory. Since the critical point is located in the limit of zero magnetic field H , current density J and frequency ω , increased applied current should drive the system further away from the transition and thus into the ohmic regime. The FFH dynamic scaling function can be written in the following form with assumed dimensionality $D = 3$ [14]:

$$\frac{E}{J} = \xi^{1-z} \chi_{\pm}(J\xi^2, \omega\xi^z, H\xi^2, \dots). \quad (1)$$

where E is the electric field.

In our measurement, the magnetic field term $H\xi^2$ can be ignored. The two remaining terms are $J\xi^2$ and $\omega\xi^z$.

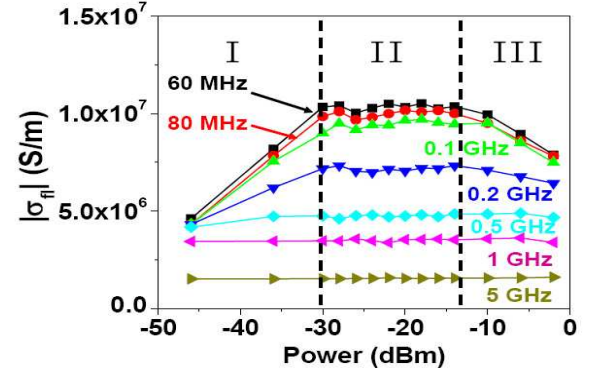


FIG. 2: (Color online) $|\sigma_{fl}|$ vs. incident microwave power at different frequencies. ($T=89.140$ K, sample xuh139 below T_c)

Qualitatively, at low frequency, $\omega\xi^z$ is small compared to $J\xi^2$ so that the applied power has more effect on the fluctuation conductivity.

To illustrate the effect of different powers, $|\sigma_{fl}|$ vs. microwave power at different frequencies is plotted in Fig. 2. The power dependence of $|\sigma_{fl}|$ varies with frequency. At low frequencies (60 MHz, 80 MHz and 100 MHz), $|\sigma_{fl}|$ vs. incident power increases first as power increases (Region I) and then saturates (Region II). At very high power, the $|\sigma_{fl}|$ decreases again (Region III). At high frequencies (> 0.5 GHz) the fluctuation conductivity is almost power independent.

The important features in Fig. 2 are that large applied power affects the fluctuation conductivity, and that even small power depresses the fluctuation conductivity at low frequency. While the high-frequency and high-power data in Fig. 2 can be explained by FFH scaling theory[14, 16, 17], the low-power low-frequency behavior is not explained by these theories alone.

The similarity between this low power and low frequency deviation and the low current density deviation in DC conductivity measurement suggests the presence of a "probed length scale" for a finite frequency. In a simple physical model, fluctuations can be visualized as closed circular vortex loops of radius r . In an infinite superconductor with no applied current, vortex loops of different size occur with different probabilities as thermal fluctuations. When a current with density J is applied, some vortex loops (with large r) will blow out to infinite size (dissipation). Some vortex loops (with small r) shrink and annihilate (no dissipation). The current density induced length scale L_J , which can be written as $L_J = (\frac{kT}{2\pi\Phi_0 J})^{\frac{1}{2}}$, [14, 25, 29] separates vortex loops into two categories, depending on their ultimate fate. The shrinking of a vortex takes time. The shrinking time depends on the size of the vortex, thus relating the size of a vortex to a time scale. In AC measurements, small frequency means that large length scales are probed, so one investigates large size vortex

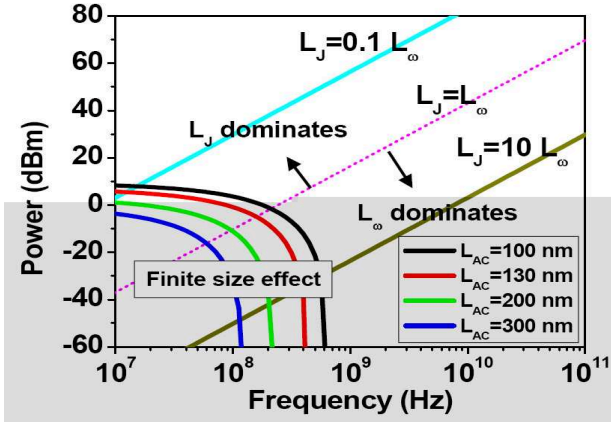


FIG. 3: (Color online) Summary of length scales and finite size effects in Corbino AC measurements of fluctuation conductivity of YBCO films near T_c . The dotted line in the figure gives the boundary $L_J = L_\omega$. At low frequency and small current density, the probed length scale L_{AC} approaches the thickness of the sample.

loops, and *vice versa*. From the order parameter relaxation time scale in time-dependent Ginzburg Landau theory[30] one can construct a frequency-induced length scale $L_\omega = (\frac{ck_B T_c}{\hbar \omega})^{1/z} \xi(0)$, where c is a constant of order 1 and $\xi(0)/\xi(T) = |T/T_c - 1|^\nu$.

In AC conductivity measurements, the probed length scale involves both frequency and current density. Among them, the smaller length scale dominates the measured fluctuation conductivity. We propose a plausible expression for the probed length scale for AC measurement L_{AC} , $\frac{1}{L_{AC}} = \frac{1}{L_J} + \frac{1}{L_\omega}$. This formula has the correct limits, and it is also consistent with the two-term FFH scaling, without the magnetic term $H\xi^2$. Finite size effects come into play when L_{AC} approaches the thickness of the film.

Fig. 3 summarizes the length scales in an AC measurement in terms of experimental quantities. In this figure, we use $\xi(0) = 5\text{\AA}$, $c = 1$ and $z = 1.5$. The dotted line in the figure gives the boundary $L_J = L_\omega$. To the right and below the dotted line, when $L_\omega \ll L_J$, the frequency induced length scale dominates, and one observes mainly frequency dependent behavior of the fluctuation conductivity. Above the dotted line, when $L_\omega \gg L_J$, current-induced nonlinear effects will dominate the behavior. This explains the features shown in Fig. 1 and Fig. 2, where the current density has less effect on the fluctuation conductivity at high frequency and a larger effect at low frequency.

At low frequency and small current density, L_{AC} may approach the thickness of the sample (d) or some other length scale that interrupts the fluctuation vortex loops. Hence deviations from the simple scaling theory are expected when $L_{AC} > d$.

In our AC measurements, we want to keep $L_{AC} < d$. Hence we choose to stay at low J but high ω . In this

region we can find the true critical behavior without getting into finite-size effect or crossover difficulties. Our previous analysis strayed out of this region and may account for the larger values of z reported before[15] and elsewhere in the literature.

With very small applied microwave power, -46dBm, and high frequency data, we investigated the frequency dependent fluctuation conductivity around T_c . We found that the determination of T_c is crucial for obtaining critical exponents. With high quality data taken at small temperature intervals (50 mK), [16] first we improved the conventional data analysis method[15] to determine T_c . We did a quadratic fit for $\log|\sigma_{fl}(f)|$ vs. $\log(f)$ and a linear fit for $\phi_\sigma(\omega)$ vs. $\log(f)$ and determined T_c through the sign of the $\log(f)^2$ coefficient of the quadratic fit, and the slope of the linear fit.[28] In addition, we developed a new method to determine T_c . Inspired by the Wickham and Dorsey scaling function $S_+(y)$ [16], we choose scaling parameters $\omega_0(T)$ and $\sigma_0(T)$ at each temperature to collapse $\phi_\sigma(T)$ vs. $\omega/\omega_0(T)$ and $|\sigma_{fl}|/\sigma_0(T)$ vs. $\omega/\omega_0(T)$ to smooth and continuous curves, without *a priori* determination of T_c or critical exponents.[20, 28] Then we extracted the critical temperature and exponents by forcing $\omega_0(T)$ and $\sigma_0(T)$ to show power-law behavior near T_c . By combining the two methods the critical temperature and exponent for sample xuh139 were determined, $T_c = 89.25 \pm 0.03\text{K}$, $z = 1.55 \pm 0.12$. [28]

The dynamic critical exponent should be sample independent. To check the results, we not only repeated measurements on the same sample, but also repeated the experiment on different samples. Films of different thickness ($d = 100\text{ nm}$ to 300 nm) were examined, and z was found to be independent of the thickness, keeping in mind the constraints of Fig. 3. Experiments on 6 samples have been done giving $z = 1.56 \pm 0.10$.

We also performed DC current-voltage characteristic measurements on the same samples.[28] Typical results are shown in Fig. 4.(with no background subtraction[31]) According to the negative curvature criterion[32], we determined the critical temperature to be $91.220 \pm 0.04\text{ K}$ and the critical exponent $z = 1.75 \pm 0.2$ from the derivative plot in Fig. 4(b). In Fig. 4, all the isotherms tend towards ohmic behavior at low current density, brought about by $L_J > d$ finite-size effects.[25] When the current density is smaller than $1 \times 10^6\text{ A/m}^2$, the sample will have only ohmic response around T_c . The -46dBm applied power in AC measurement corresponds to a maximum current density of $2.2 \times 10^5\text{ A/m}^2 (< 1 \times 10^6\text{ A/m}^2)$. This means that for -46dBm incident power $L_J > d$, verifying a feature of Fig. 3, and suggesting that one-parameter scaling should work when $L_\omega < L_J, d$. Hence it is appropriate to determine T_c and critical exponents with AC data at -46dBm applied power.

The difference of T_c between DC and AC measurements is due to the different thermometer positions and temperature control techniques of the two systems. The resistance vs. temperature plots from the AC and DC

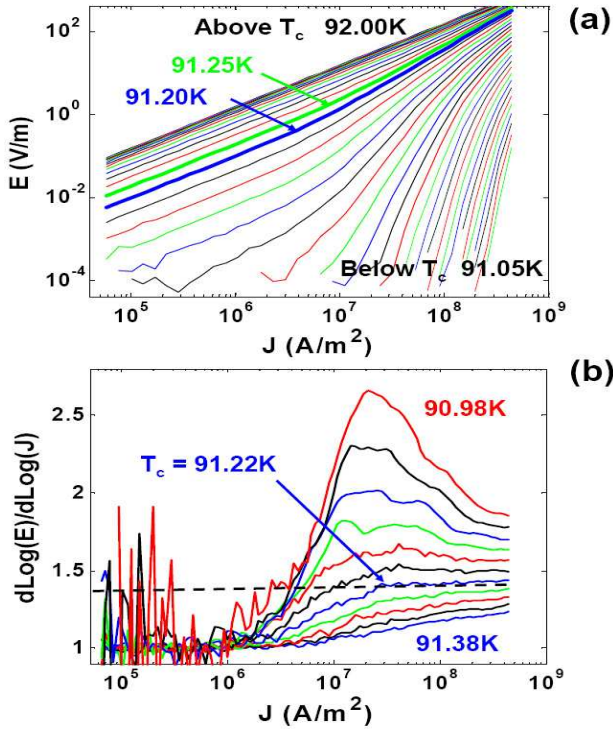


FIG. 4: (Color online) DC current-voltage characteristics measurement, performed after the AC experiment on xuh139 in zero magnetic field. (a) E - J isotherms (50 mK apart), (b) $d \log E / d \log J$ vs. J derivative plot (40 mK apart).

experiment have a 2.0 K temperature offset, which is the difference of the determined T_c from these two methods. Hence the determined T_c from the two methods are consistent.

Performing DC measurements on the same film after AC measurements involves more processing steps than a DC measurement alone, and may result in additional disorder in the sample. Disorder and heating leads one to systematically choose a lower temperature isotherm as T_c and then obtain a larger value of z . [28, 31] We carefully repeated the measurements on different YBCO films and found that the sample quality does affect the obtained value of z from the DC experiment. [28] However, for films with high T_c , sharp transition and small resistivity, we obtained a value of $z = 1.56 \pm 0.08$ from DC measurement, which is consistent with the AC result $z = 1.55 \pm 0.15$. In addition, DC measurements carried out the same way on high-quality crystals also gave $z \approx 1.5$. [31]

In this work, we focused on temperatures very close to T_c (the reduced temperature $t < 0.004$) and finite-frequency scaling. In this temperature range, due to the influence of the finite size effect at low frequencies the static critical exponent ν cannot be determined. [31]

To conclude, using two different measurement meth-

ods, we studied the dynamic fluctuation effects of $YBa_2Cu_3O_{7-\delta}$ thin films around T_c . The combination of AC and DC measurements precisely determined the dynamical scaling exponent $z = 1.55 \pm 0.08$, which suggests the superconducting to normal phase transition of high- T_c materials is consistent with model E-dynamics. [33]

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